Effect of speed reduction on particle emissions of ships

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Introduction

Speed (and power) reduction, "slow steaming" (SS) of vessels is increasingly researched as one means of saving fuel and enhance global warming. Besides GHG, SO_x and NO_x reductions changes in other emissions are probable. Effects on aerosol emissions are more complex. The importance of these is due to the fact, that impact of BC in the atmosphere has increased */Bond et al. 2013/,* and a delicate environment for increasing marine traffic is the Arctic. For particle emissions changes are combinations of variations in engine power and fuel quality */Agrawal et al. 2010, Petzold et al. 2010, Lack et al. 2011, Khan et al. 2012/*. The effect of fuel quality will be boosted as the global, EU, SECA and local regulations for fuel sulphur are finalized between 2015-2025, to 0.5 w-% and 0.1 w-% sulphur caps. As regards fuel quality it has not been verified that e.g. soot emissions would be reduced due to current regulations.

In this study the effects of lowering the speed of a vessel and/or power of the engine especially on particulate number (PN) and solid carbonaceous emissions were studied. The emission sources were 4-stroke marine engines, and fuel sulphur contents 1.0 and 0.9 % S. For the vessel speed reduction – fuel oil consumption (SFOC) relationships both 4-stroke and 2-stroke engine equipped ship operations were estimated.

Experimental

The propulsion sources are described in **Table 1**. The fuel for the vessel was FO380 with maximum currently SECA allowed S content, 1.0 %. Practicable operational load range for this engine was circa 35-90 %. The engine for soot studies was a constant speed, turbocharged marine engine HFO with 0.9 % S.

Table 1 *The vessel / engine studied for particle emissions and their characteristics.*

Vessel / Engine	Engine power range studied load-%	HFO fuel %-S	Characteristic studied
IMO NOx tier II compliant, 4-stroke, medium speed, derated, @ propeller curve, 4x7600 kW, 500 1/min, my 2011	10 - 100	1.0	Vessel speed - power relationship Particle number (PN) emission Particle size
NOx tier "0", 4-stroke, medium speed, rated speed 750 1/min, 1600 kW, my 1995	10 - 100	0.9	Solid carbon (total C-SOF), in-stack EC, in-stack, diluted

Methods

- Exhaust particle numbers (PN) and sizes: electrical low pressure impactor (ELPI), D_a range 20 - 10000 nm; dilution ratio (Dr) 30 – 100.

- Heated (300°C) dilution air to be devoid of the volatile share of particle PN, generated from VOCs and H_2SO_4 in exhaust cooling and sample dilution
- In-stack PM filters sampled from the hot exhaust according to ISO9096:2003. The stack temperature range 210°C - 345°C (10 & 100 % loads): total C-SOF & EC analyses
- ISO8178:2006 PM filters from diluted (Dr 11-12) and cooled (T 42-52°C) exhaust: EC analyses
- Non-extractable carbonaceous matter (total C – soluble organic fraction SOF): Total C analysis thermogravimetrically with a Vario-Max CHN analyzer; SOF Soxhlet extracted with DCM
- EC analysis: Thermal-optical OCEC analyzer (TOA) by Sunset Inc. , NIOSH procedure
- Gaseous emissions (NO, NO_2, CO_2, SO_2 etc.): FTIR
- In-situ measured speed-power–relationships for the studied vessel. Information of the SFOC vs. load and exhaust mass flow rates in real ship operation by the shipyard or engine manufacturer. Other speed-power/FOC relationships for vessels with 4- and 2-stroke engine based on Ship Track Emission Assessment Model (STEAM) */Jalkanen et al. 2012/.*

Results & discussion

Speed reduction

The power need of the vessel is coarsely proportional to the third power of the speed, and the fuel oil consumption (FOC) over the total cruise is proportional to speed squared, or slightly higher. The speed – power relationships of the ro-ro ferry is in **Figure 1**. The correlation varies, as speed is susceptible to environmental conditions like surges and wind, cargo and the combination of engines in use. The environmental conditions affect the more the lower is the power and the speed. In emission calculations the average function of **Figure 1** was used. In engine load lowering, unless derating, SFOC changes due to the non-optimal operating conditions. The SFOC rise is in **Figure 2**. Power lowering from 85 % to e.g. 35 % load increased SFOC 6 – 12 % in the two cases studied for 4-stroke engines.

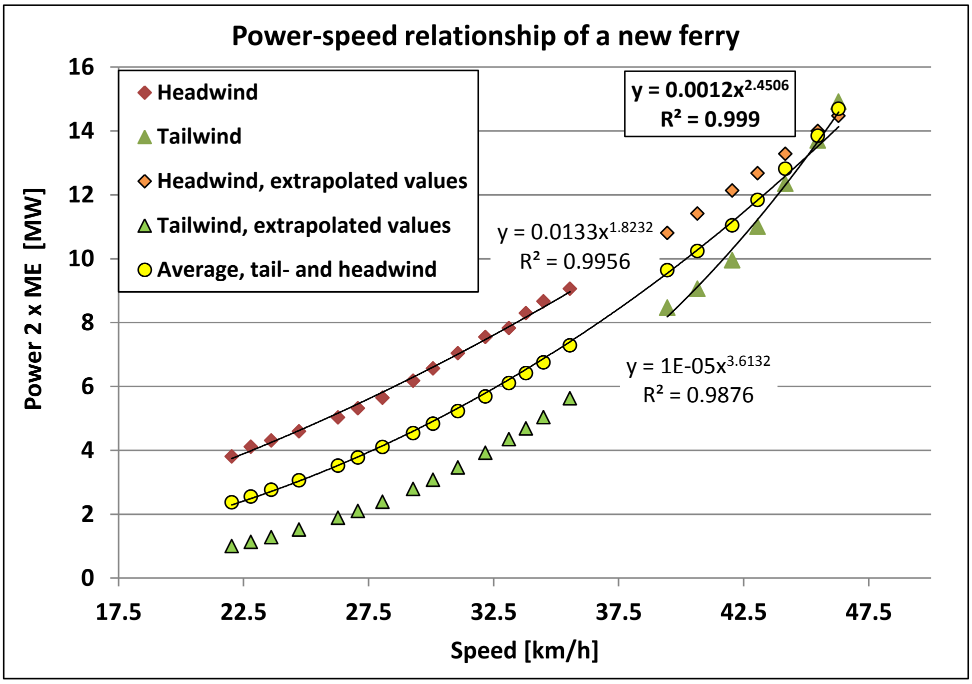

Figure 1 *Effect of vessel speed reduction on engine power demand. IMO NO_x Tier II compliant ferry with circa 30 MW main engine (ME) power (plus four auxiliary engines).*

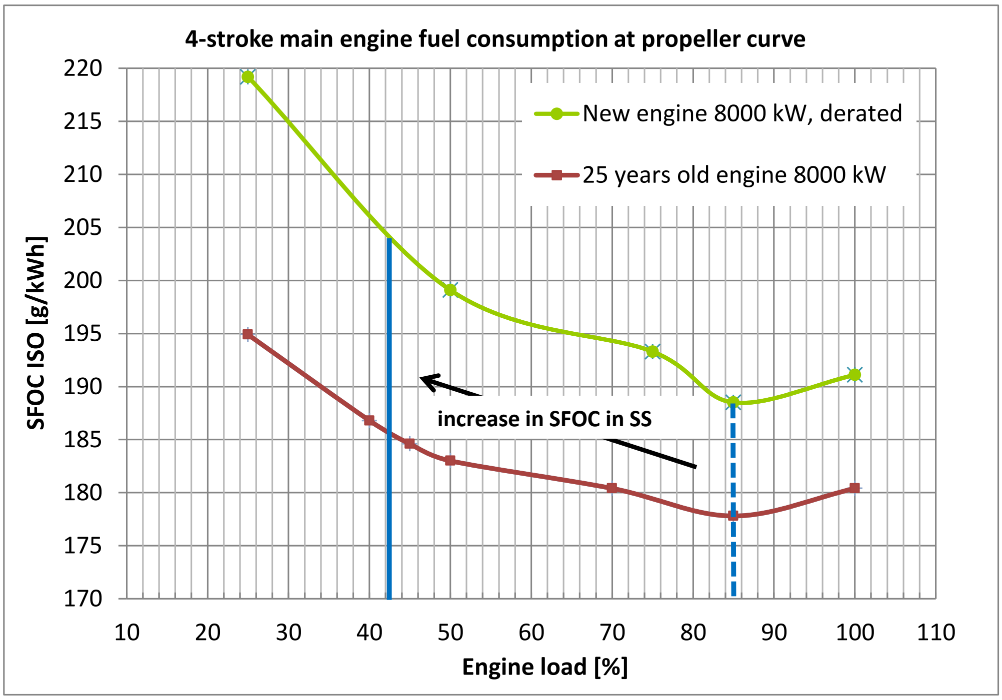

***Figure 2** Increase in fuel oil consumption (SFOC) in slow steaming. Example: 50 % load reduction.*

For a vessel with multiple MEs and mechanical power transmission there are two ways for speed lowering, see **Table 2**. Either all main engines are at a low engine load or unnecessary engines are swiched-off and normal engine loads are applied on active ones. Application of normal (75-85%) engine load on the active engines results in optimal diesel engine operation. In this case relatively high amounts non-volatile particles (PN/s) may be produced in harbors, as seen from **Figure 3** below. Lower loads (25-50%) may also lead to other side-effects like increased unit emissions. This is reality with vessels with only one ME in SS, **Table 2**.

***Table 2** Effect of vessel speed reduction on power and FOC demand for a 2-stroke and 4-stroke engine equipped ships.*

Vessel type	**Engines**	**Engines in-use** ME share %	**Reduction** Speed	**Power**$^{1), 2)}$ % of maximum	**FOC**$^{3)}$ per trip %
Cargo	**2-stroke**	100	0 %	88	100
Containership	(power lowering)	100	10 %	58	84
(global transport)		100	25 %	30	55
		100	50 %	9	22
Ferry	**4-stroke**	100	0 %	75	100
Cruising ship	(turning off engines	75	10 %	64	90
Ro-ro/	or power lowering)	100	25 %	50	73
Ro-pax		50	25 %	50	69
(short-sea, overseas)		100	50 %	7	38
		50	50 %	7	35

$^{1)}$ without shaft generator, $^{2)}$ windless conditions , $^{3)}$ SFOC penalty assumed in load reduction

Emissions

In engine load range of 35-90 % of the vessel non-volatile PN emissions (per h) were reduced with the load, **Figure 3**. As the ship was slowed down from the typical cruising load of 80-90% and 43.5-

45.5 km/h speed to 35 % load and to a 29 % lower speed (31.5 km/h), the PN emission (1/h) went down in parallel and linearly with the power. Power reduction was circa 59 % and PN reduction 56-57 %. The result is analogous with those reported for PM in */Lack et al. 2011, Khan et al. 2012/*. The reduction is less due to our target of minimizing the labile effect of volatile constituents (VOC, SO_4) on particles. Over power range 35–100 % the PN size distributions were identical in shape and position in the size D_a axis. Hence, the approximations made for PN emissions are coarsely applicable to also particle mass comparisons. From the earlier studies of particle emissions of the same vessel */Lappi et al. 2012/,* it was learned that the non-volatile PN emission (per h) was more strongly a function of fuel quality, and to a much less extent on load.

Reduction in power drop 80-90 % -> 35 % in SS				
PN D_p > 55 nm emission			Speed	Power
#/h 57 %	#/km 40 %	Voyage 40 %	29 %	62 %

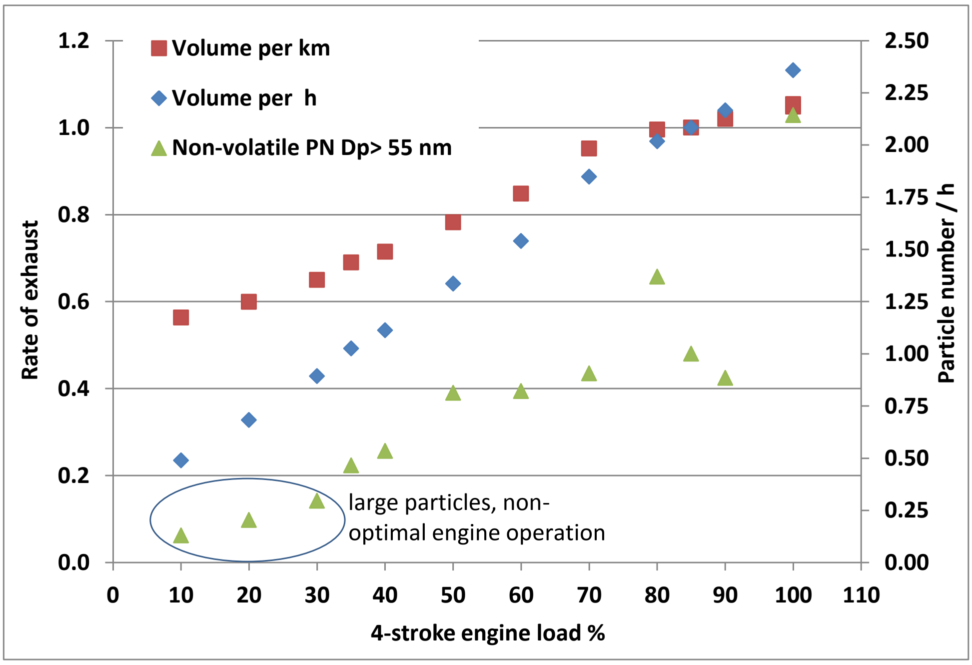

***Figure 3** Relative volumetric emission rates and non-volatile particle numbers (PN) in engine load / vessel speed reduction. 4-stroke marine engine, fuel HFO 1.0 % S.*

In slow-down by lowering the (4-stroke) power the effect on solid/elemental carbon (EC) emission rates (g/h) is seen in **Figure 4**. Non-extractable carbon (in-stack) and EC (ISO8178) emissions were independent on load remaining relatively constant over the practicable engine load range. As emission factors (g/kWh) there is naturally a considerable rise with load lowering. Reduction in engine power of 50 % (e.g. from 85 % to 42-43 %) results in 20-25 % speed reduction, depending on e.g. climatic conditions. This means that the relative solid carbonaceous emission per voyage (kg carbon) will be 20-25 % higher and the emission factor (g/kWh) 50 % higher for the lowered load. The trend was identical, within measurement accuracy and measurement method, for respective emissions from a high sulphur fuel (2.4 % S) and MGO; no marked change in solid carbonaceous emission rate (per h) with load lowering.

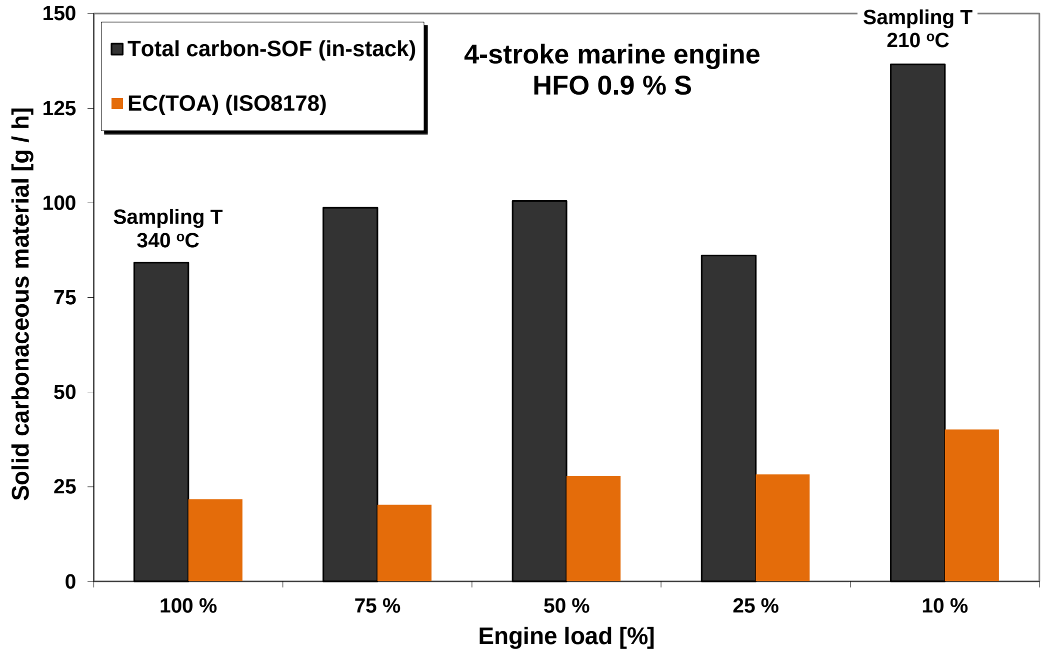

Figure 4 *Effect of power reduction on solid carbonaceous emission from filter measurements. 4-stroke marine engine, constant speed. Black bar = carbonaceous material after removal of soluble organic material (SOF), orange bar = pure elemental carbon (EC) analysed by TOA.*

EXAMPLE OF YIELDS OF SPEED REDUCTION FOR A 4-STROKE ENGINE EQUIPPED SHIP (FUEL S 1 %) Outcomes	
	• Speed reduction of 20-25 % (depending on environmental conditions) • Power reduction 50 % • Non-volatile particle number (PN) reduced to a marked extent over the voyage • Soot emission per time constant • Net fuel consumption reduction 44-47 % • Very marked reduction in NO_x emissions per trip, relative benefit higher than that of enegy saving • CO_2 and SO_x emission reductions directly proportional to reduction in fuel consumption
Penalties	
	• Inferiour SFOC, by 6-12 %
	• Moderate increase in soot emission over the voyage; inversely proportional to speed reduction
	• Reduced efficiency of the engine propeller (in engine drop-off mode)
	• Elongated voyage times

Conclusions

In moderate speed lowering of a new 4-stroke engine ship significant fuel savings are achievable with parallel, significantly reducing non-volatile PN emissions (per voyage).

Solid carbonaceous/EC emission (per hour) was almost engine load independent and constant for a 0.9 % S fuel. Hence, moderate increase in absolute amount of these emissions in power lowering.

Diversity and scatter of published BC/EC/soot emission results related to both speed (power) reduction and fuel quality require more analysis of the methodologies used in their determination, and possibly differentiation of vessel types as soot emission sources.

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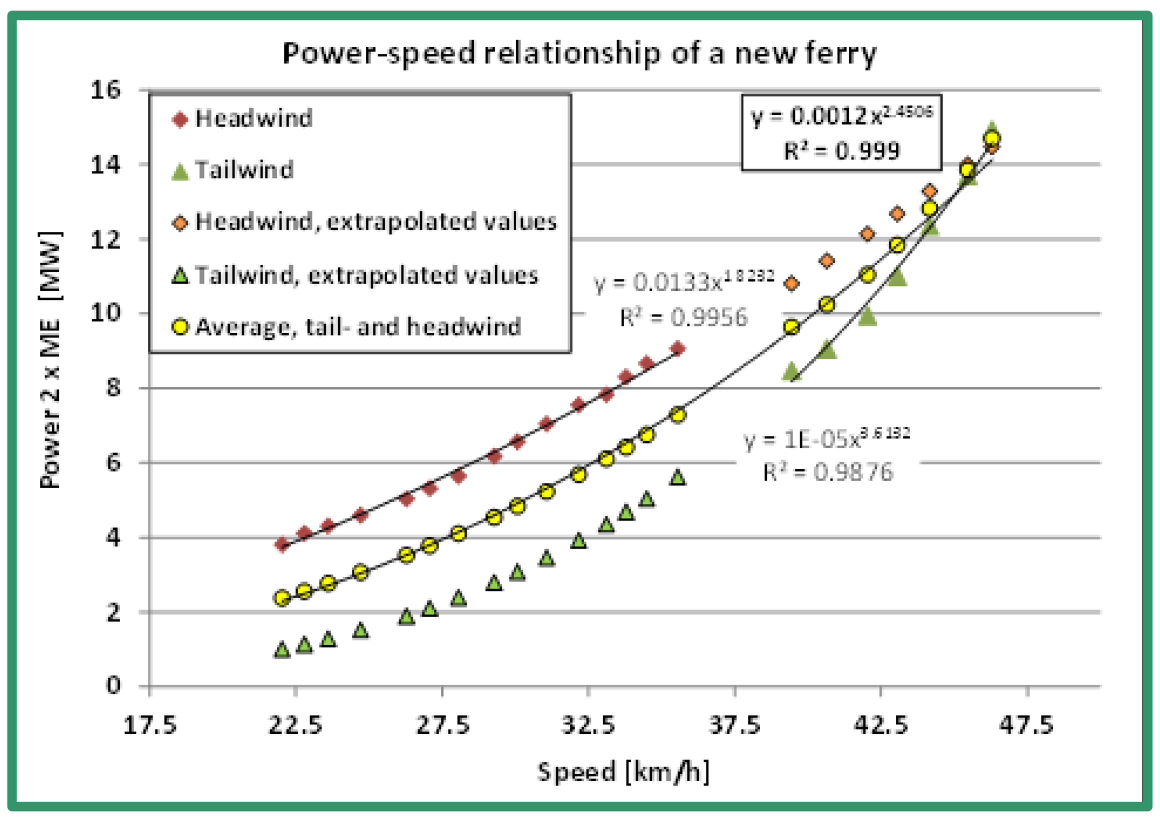
The power need of a ship is coarsely proportional to the third power of the speed, and (FOC) over the voyage proportional to speed squared, or slightly higher. The speed – power relationships of the ro-ro ferry is in **Figure 1**. Speed is susceptible to environmental conditions like surges and wind, cargo and the combination of engines in use. Effects of environmental conditions intensify with low power and speed. In engine load lowering SFOC may rise due to the non-optimal operating conditions; power lowering 85 % → 35 % increased SFOC 6 – 12 % in two cases studied for 4-stroke engines.



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With multiple MEs and mechanical power transmission there are two ways for speed lowering, either all main engines at a low load or unnecessary engines switched-off and normal loads for the others, **Table 2.** Normal (75-85%) engine load applied to the active engines results in optimal diesel engine operation. In this case relatively high amounts non-volatile particles (PN/s) may be produced in harbors, as seen from **Figure 2**. Lower loads (25-50%) may also lead to other side-effects like increased unit emissions. This is reality with vessels with only one ME in SS, Table 2.

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Cargo Containership (global transport)	**2-stroke** (power lowering)	100	0 %	88	100
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Ferry Cruising ship Ro-ro/ Ro-pax (short-sea, overseas)	**4-stroke** (turning off engines or power lowering)	100	0 %	75	100
		75	10 %	64	90
		100	25 %	50	73
		50	25 %	50	69
		100	50 %	7	38
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1) without shaft generator, 2) windless conditions , 3) SFOC penalty assumed in load reduction

Emissions

As the ship was slowed down from the typical cruising load of 80-90% and 43.5-45.5 km/h speed to 35 % load and to a 29 % lower speed (31.5 km/h), the PN emission (1/h) went down in parallel and linearly with the power. Power reduction was circa 59 % and PN reduction 56-57 %. The result is analogous with those reported for PM in */Lack et al. 2011, Khan et al. 2012/.* Reduction is less due to the minimized volatile constituents (VOC, SO_4) on particles. Over power range 35–100 % the PN size distributions were identical in shape and position in the size D_a axis. Hence, the approximations made for PN emissions are coarsely applicable also to particle mass comparisons. Earlier it was learned */Lappi et al. 2012/* that non-volatile PN emission (per h) was more strongly a function of fuel quality than load.

In slow-down the effect on carbonaceous emission rates (g/h) is seen in **Figure 3**. Non-extractable carbon (in-stack) and EC (ISO8178) emissions were independent on load, remaining relatively constant over the practicable engine load range. As emission factors (g/kWh) there is a considerable rise with load lowering. Reduction in engine power of 50 % (e.g. from 85 % to 42-43 %) results in 20-25 % speed reduction, depending on e.g. climatic conditions. Hence, the relative solid carbonaceous emission per voyage (kg) will be 20-25 % higher and the emission factor (g/kWh, g/kg fuel) 50 % higher for the lowered load. The trend was the same for respective emissions from a high sulphur fuel (2.4 % S) and MGO; no marked change in solid carbonaceous emission rate (per h) with load lowering.

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PN D_p > 55 nm emission			Speed	Power
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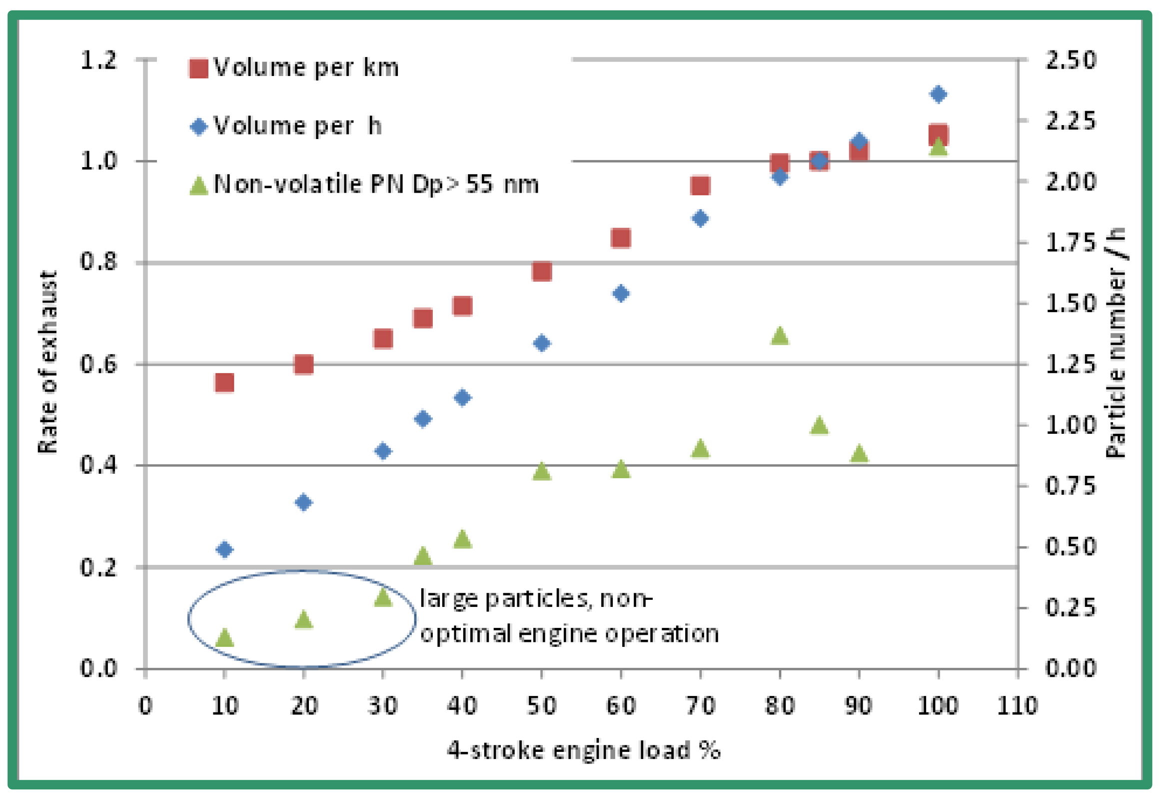

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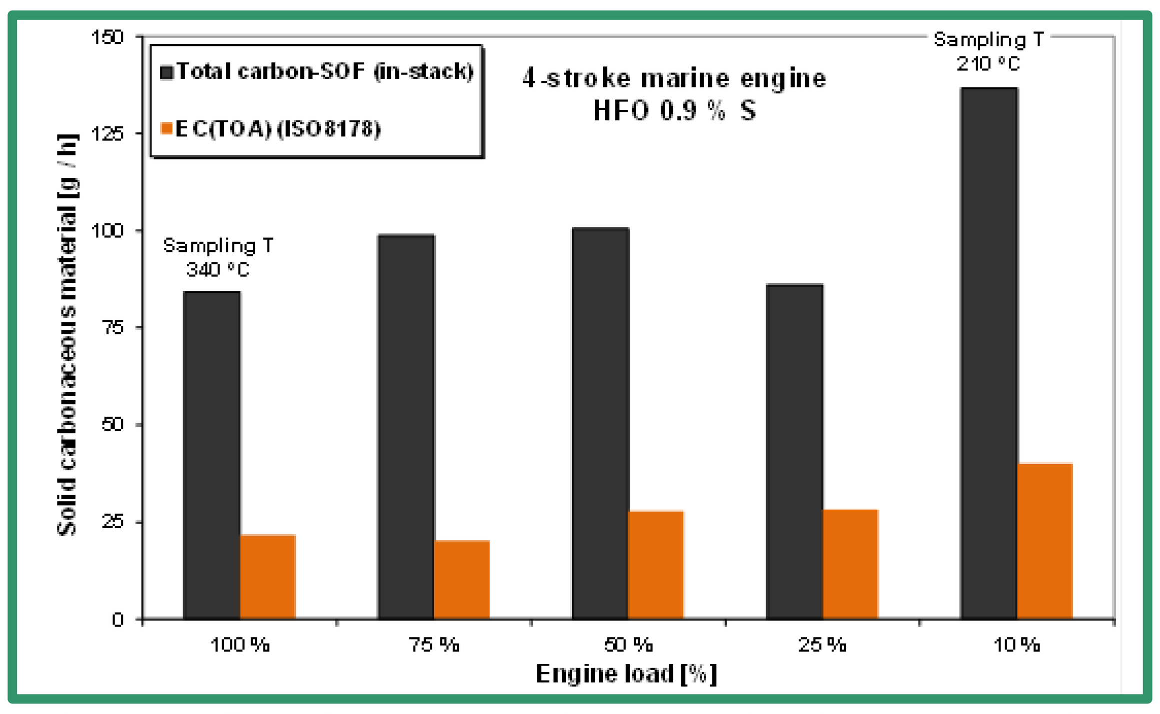

Figure 3 *Effect of power reduction on solid carbonaceous emission from filter measurements. Constant speed engine.*

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Outcomes

- Speed reduction of 20-25 % (depending on environmental conditions)
- Power reduction 50 %
- Non-volatile particle number (PN) reduced to a marked extent over the voyage
- Soot emission per time constant
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- Very marked reduction in NO_x emissions per trip, relative benefit higher than that of energy saving
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Penalties

- Inferiour SFOC, by 6-12 %
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- Reduced efficiency of engine propeller (drop-off)
- Elongated voyage times

Conclusions

In moderate speed lowering of a new 4-stroke engine ship significant fuel savings are achievable with parallel, markedly reduced non-volatile PN emissions (per trip). Solid carbonaceous/EC emission (per hour) was almost engine load independent and constant for a 0.9 % S fuel. Speed dependent increase in absolute amount of these emissions is met in power lowering.

Diversity and scatter of published BC/EC/soot emission results related to both speed (power) reduction and fuel quality require more analysis of the methodologies used, and possibly differentiation of vessel types as soot emission sources.

References

See extended summary.

Baltic Sea Region Programme 2007-2013
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